Improvement of Center Segregation in Continuously Cast Blooms by Convex Roll Soft Reduction

Liang Li, Xiao Zhao, Peng Lan, Zhanpeng Tie, Haiyan Tang and Jiaquan Zhang

Abstract A two-dimensional finite element model has been established based on thermal–mechanical coupled calculation for the determination of soft reduction amount by convex roll during bloom continuous casting. The shrinkage of the mushy zone is then calculated based on mass conservation during solidification. The total shrinkage area is about 75 mm^2 for the 180×240 mm^2 bloom with a casting speed of about 1.25 m min^{-1}. The reduction efficiency of the convex roll is calculated on basis of the visco-elastic-plastic deformation behavior of mushy zone. It decreases linearly from 31.7 to 4.7% when the center solid fraction of the reduction location increases from 0.3 to 0.6. The maximum stress is observed on the bloom surface where the strand contacts to the chamfer of the convex roll, while the maximum plastic strain appears in the inner-arc mushy zone. The total soft reduction amount suggested by the present model is 6.06 mm. It is noticed that the center segregation and "V" segregation have been improved remarkably by soft reduction with convex rolls.

Keywords Continuous casting · Convex roll soft reduction · Segregation · Finite element model

Introduction

To meet the increasing inner quality demands for special steel, the newly developed convex roll soft reduction (CRSR) technology has been applied to improve the centerline segregation and porosity in continuous casting. Unlike the traditional soft reduction technology, the CRSR just makes the middle part of the strand contact to the top roll. Low power and high efficiency are the most obvious advantage of the CRSR. Ogibayashi et al. [1] conducted soft reduction tests on blooms using three

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types of roll shapes where the center solid fraction was between 0.2 and 0.7, and observed that "V" segregation almost disappeared and center segregation was minimized with a proper reduction rate. Okimori et al. [2] made an optimization on the shape of the convex roll for the large size bloom soft reduction in the final stage of solidification, and the results showed that there was a significant improvement for the porosity and internal crack in the bloom. Isobe et al. [3] combined the CRSR with the technology of solidification structure control, and found that the CRSR is able to decrease the degree of segregation further with an expended equiaxed zone. Moon et al. [4] also proposed that the centerline segregation was decreased significantly when the CRSR was employed in continuous casting. However, it is also noticed that the internal crack is more apt to occur in the bloom with CRSR, especially in the loose-side zone. For the sake of appropriate application of CRSR, it is quite necessary to investigate the relationship between reduction parameters and the matrix deformation behavior. Unfortunately, it is still not well debated in previous works [1–3]. The present study is aimed to develop a finite element model to determine the soft reduction amount with thermal–mechanical coupled calculation, and reveal the distribution of the stress and strain in the bloom during continuous casting with CRSR. The application of the predicted result shows a visible improvement on the segregation and porosity.

Model Description

Heat Transfer Model

In this study, the CRSR technology is applied in a $180 \times 240\ \text{mm}^2$ bloom continuous casting. The model domain is one half of the transverse section of the bloom. The two-dimensional transient heat conduction, Eq. (1), is solved for the temperature distribution:

$$\rho C_{eff}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y}) \tag{1}$$

where ρ is density of steel, C_{ceff} is equivalent specific heat, T is temperature, t is time, λ is thermal conductivity, and x and y are along strand width and thickness, respectively.

According to the heat transfer characteristic in the continuous casting, the boundary conditions of heat transfer are divided into three parts: mold, secondary cooling zone, and air cooling zone. The heat flux could be described as follows:

$$q_{\text{mold}} = A - B\sqrt{t};\ q_{\text{sec}} = h_{\text{sec}}\left(T_{surf} - T_{amb}\right);\ q_{\text{air}} = \sigma\varepsilon\left(T_{surf}^4 - T_{amb}^4\right) \tag{2}$$

where q is the heat flux of the bloom surface center, A and B are coefficients depending on the mold cooling conditions, t is time on the mold, h_{sec} is the equivalent convection coefficient related to water flow, σ is Stefan–Boltzmann constant and ε is the emissivity of steel.

Deformation Model

A 2D thermal–mechanical model has been developed to simulate the soft reduction process during the continuous casting. The following assumptions are made here:

(1) The plain stress condition is satisfied.
(2) The ferrostatic pressure is applied to the nodes on solidification interface.
(3) The rolls are rigid.
(4) The solidified shell is regarded as visco-elastic-plastic material.

The total strain rate is divided into elastic, inelastic, and thermal components

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{ie} + \dot{\varepsilon}_{th} \tag{3}$$

where inelastic strain includes the combined effects of plastic strain and creep.

Material Properties

The steel grade in the paper is C92, a type of tire cord steel. The main compositions are 0.92%C, 0.20%Si, 0.37%Mn, 0.008%P and 0.004%S. Figure 1a shows the faction of liquid phase and solid phase as a function of temperature during solidification by a micro-segregation model [5]. Considering the convective heat in the liquid region, the thermal conductivity of liquid phase is increased, as shown in Fig. 1b. The density, Young's Modulus [6] and Poisson's ratio [7] of C92 are also shown in Fig. 1c, d.

For γ-Fe, the following constitutive model is employed [8]:

$$\dot{\bar{\varepsilon}}_{in-\delta}(1/s) = f_{pct}\left|F_\gamma\right|^{f_3-1} F_\gamma \exp\left(\frac{-4.465 \times 10^4}{T(K)}\right) \tag{4}$$

where accumulated inelastic strain rate, $\dot{\bar{\varepsilon}}$, acts as the structure parameter, F_γ acts as a strain-hardening back-stress term to achieve the Bauschinger effect.

$$\begin{aligned}
F_\gamma &= C\bar{\sigma} - f_1\bar{\varepsilon}_{in}\left|\bar{\varepsilon}_{in}\right|^{f_2-1}\\
f_1 &= 130.5 - 5.128 \times 10^{-3} T(K)\\
f_2 &= -0.6289 + 1.114 \times 10^{-3} T(K)\\
f_3 &= 8.132 - 1.54 \times 10^{-3} T(K)\\
f_{pct} &= 4.655 \times 10^4 + 7.14 \times 10^4(\text{pct C}) + 1.2 \times 10^5(\text{pct C})^2
\end{aligned} \tag{5}$$

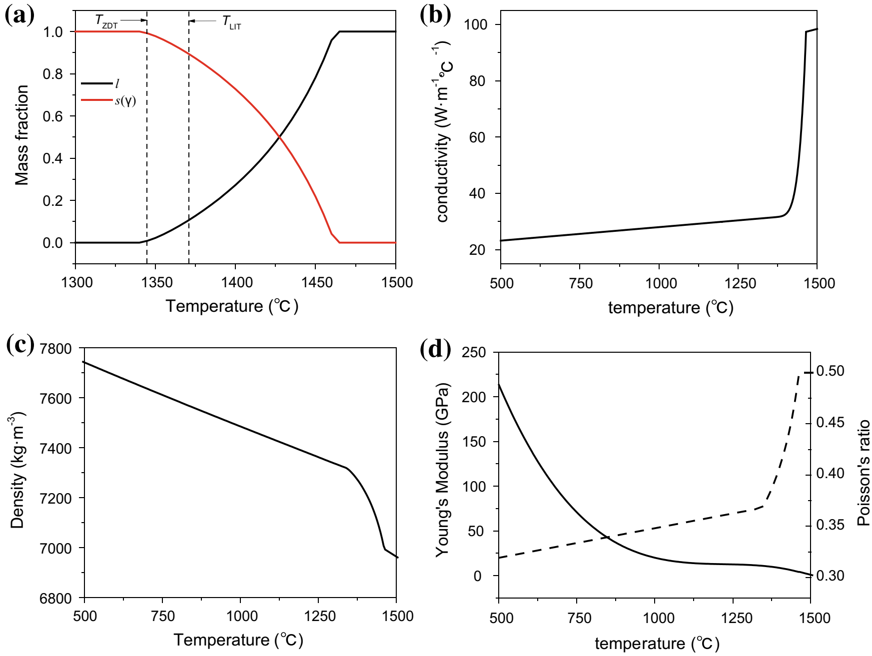

Fig. 1 Phase fraction and material properties of C92 steel: **a** phase fraction, **b** conductivity, **c** density, **d** Young's modulus and Poisson's ratio

where C is equal to 1 for tensile strain or -1 for compression strain.

Results and Discussion

Model Validation

The C92 steel was continuously cast at 1.25 m min^{-1} with a casting temperature of about 1488 °C. In order to verify the model, a nail shooting experiment was carried out in the plant. Then, the shell thickness and surface temperature of the bloom was both measured. Figure 2 shows the comparison between the predicted and measured results. The relative error of surface temperature is less than 1.82%, while that of the thickness is less than 2.37%. It also can be seen that the solidification length of the casting is 14.6 m.

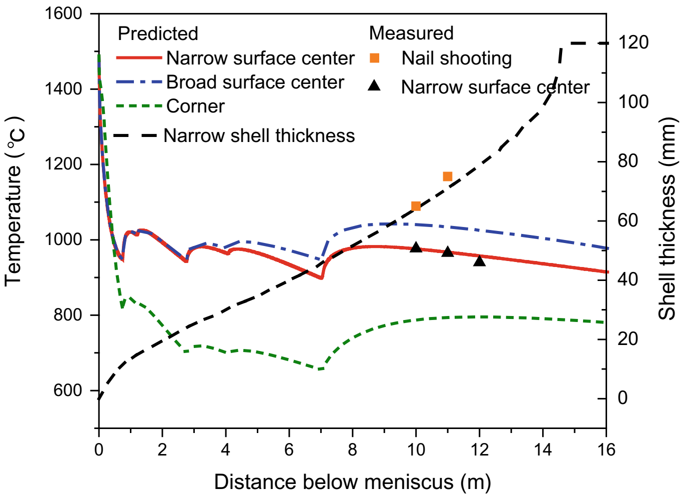

Fig. 2 Comparison between the predicted and measured surface temperature and shell thickness

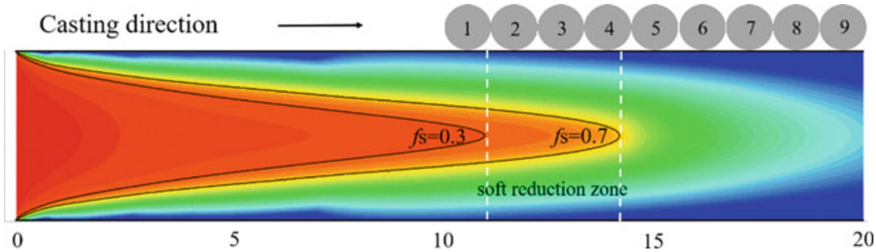

Fig. 3 Temperature distribution on longitudinal section of the bloom

Solidification Shrinkage

In order to reduce the centerline segregation and porosity in the bloom, the soft reduction was usually applied where the center solid fraction was between 0.3 and 0.7 [9, 10].

Figure 3 shows the temperature distribution on bloom longitudinal section by reconstructing the simulation result. It can be seen that the soft reduction position is located in the region about 11.7–14.1 m from the meniscus. When the center solid fraction of the bloom is large than 0.3, the soft reduction is used to compensate the further solidification shrinkage. This solidification shrinkage could be calculated by the heat transfer model as follows:

Take a square element from the bloom, its mass could be calculated as

$$M = \rho(x, y) \cdot l_i^2 \cdot 1 \tag{6}$$

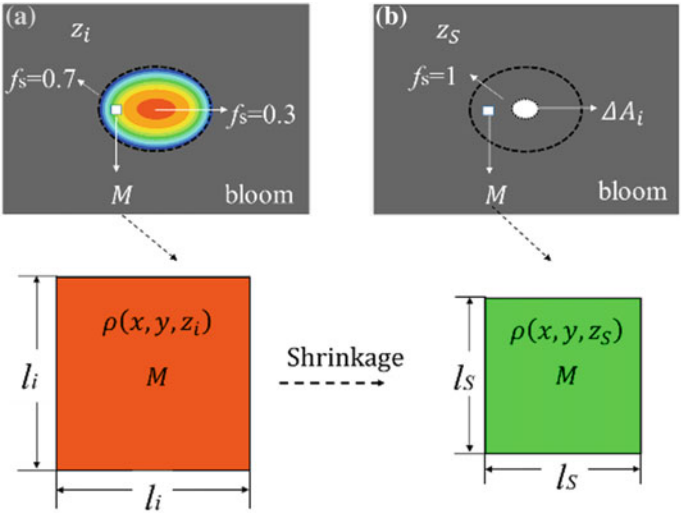

Fig. 4 Schematic to calculate the solidification shrinkage of mushy zone

where x and y are the coordinates of element, and represent the width and thickness direction, respectively, ρ is steel density function which is related to temperature and l_i is the length of the square element in each dimension (Fig. 4).

Assuming no liquid compensation in this zone, the mass of the square element after solidified completely could be calculated as

$$M = \rho_s \cdot l_s^2 \cdot 1 \tag{7}$$

Then, shrinkage area of the square element on the transverse section, Δa, could be calculated as follows:

$$\Delta a_\mathrm{i} = l_i^2 - l_s^2 = l_i^2 \cdot \left(1 - \left(\frac{\rho(x, y)}{\rho_s}\right)\right) \tag{8}$$

Therefore, the total solidification shrinkage area of the mushy zone on the bloom transverse section, ΔA_i, could be calculated by the following equation:

$$\Delta A_i = \int_0^Y \int_0^X \left(1 - \left(\frac{\rho(x, y)}{\rho_s}\right)\right) dxdy \tag{9}$$

where X is the width of mushy zone and Y is the thickness of the mushy zone. The results are shown in Fig. 5. It can be seen that the total solidification shrinkage area of the mushy zone ΔA_i decreases almost linearly along the casting direction in the

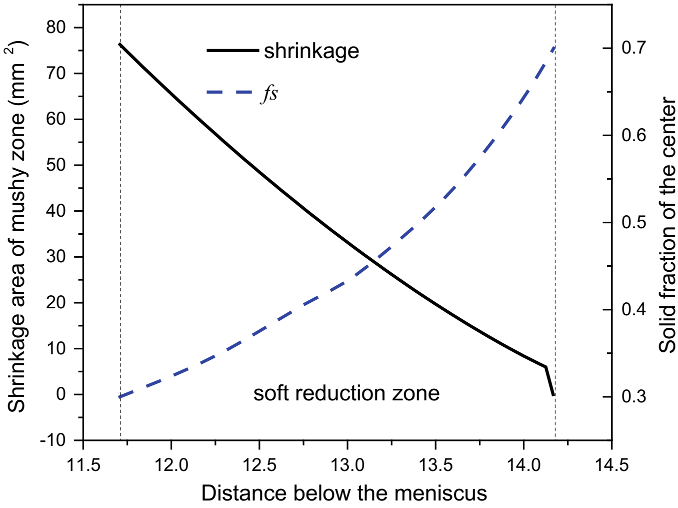

Fig. 5 Solidification shrinkage area of the mushy zone on the bloom transverse section

soft reduction zone. The total solidification shrinkage area on the bloom transverse section is about 75 mm^2.

Reduction Efficiency of Convex Rolls

The deformation behavior of the bloom on the transverse section in CRSR process is shown in Fig. 6. The soft reduction efficiency η_i is introduced to describe the relationship between the soft reduction amount on the bloom surface (R_{i}) and the actual deformation of mushy zone inside the bloom (ΔB_i). According to the work by Cheng et al. [11], the soft reduction efficiency η_i could be expressed as

$$\eta_i = \frac{\Delta B_i}{\Delta S_i} = \frac{\Delta B_i}{R_i \cdot L} \tag{10}$$

where the ΔS_i is the surface reduction area on the transverse section of the bloom.

In the present study, 32 cases were simulated including four different reduction positions ($fs_{\mathrm{center}} = 0.3$, 0.4, 0.5, 0.6) and eight different reduction amounts (0.1, 0.5, 1, 2, 4, 6, 8, 10 mm). The results are shown in Fig. 7. It can be seen that the soft reduction efficiency gradually increases within the soft reduction amount between 0 and 2 mm. However, it keeps constant when the soft reduction amount is above 2 mm. When the center solid fraction increases from 0.3 to 0.6, the maximum soft reduction efficiency decreases from 31.7 to 4.7%, while the minimum decreases from 16.4 to 2.1%.

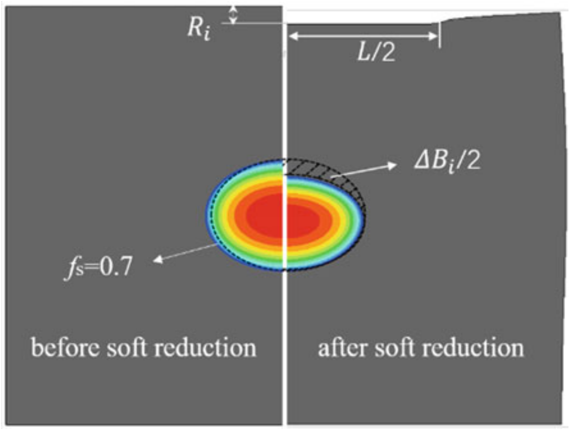

Fig. 6 Schematic of the CRSR process for bloom

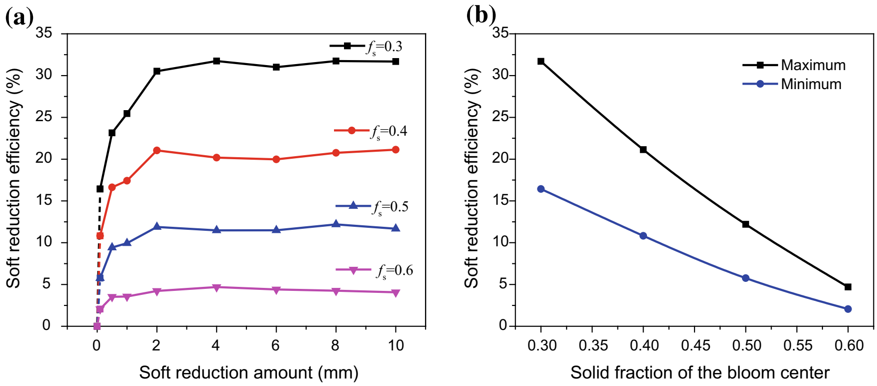

Fig. 7 Soft reduction efficiency of the bloom with convex rolls

The stress and strain distributions of the bloom transverse section during CRSR are shown in Fig. 8. It is seen that the maximum stress is observed on the bloom surface where the strand contacts to the chamfer of the convex roll, while the maximum equivalent plastic strain appears in the mushy zone of the bloom center. In addition, it is noted that the distribution of stress and strain is the transverse section is not horizontal symmetrical. The deformation is more concentrated in the inner-arc part. It suggests that the internal crack is more likely to occur in this zone if the reduction amount is overlarge (Fig. 9).

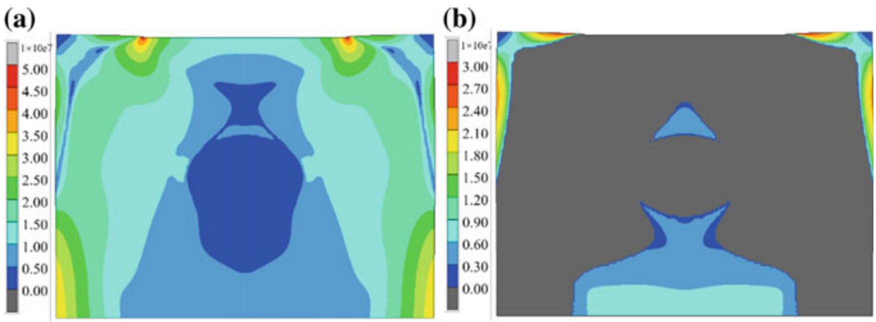

Fig. 8 Stress distribution of the bloom during the soft reduction with convex rolls ($fs = 0.3$, SR amount = 2 mm): **a** equivalent of stress, **b** major principle tensile stress (unit: Pa)

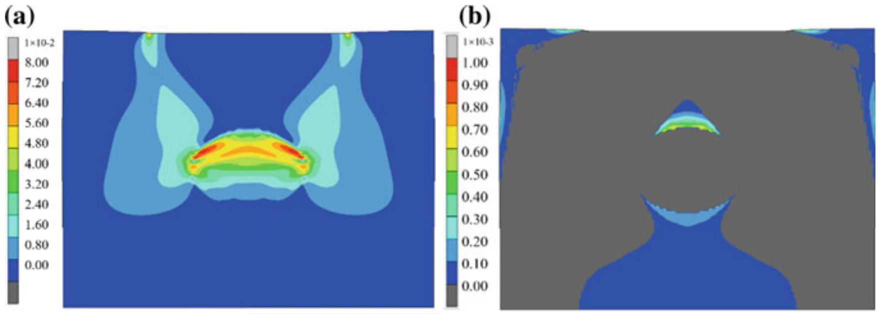

Fig. 9 Strain distribution of the bloom during the soft reduction with convex rolls ($fs = 0.3$, SR amount = 2 mm): **a** equivalent of plastic strain, **b** major principle tensile plastic strain

Soft Reduction Amount

The deformation of the mushy zone (ΔB_i) should be equal to the solidification shrinkage area (ΔA_i) to improve bloom center quality. Then, the soft reduction amount on the bloom surface (R_i) could be expressed as

$$R_i = \frac{\int_0^Y \int_0^X \left(1 - \left(\frac{\rho(x,y)}{\rho_s}\right)\right) dxdy}{\eta_i \cdot L} \tag{11}$$

The soft reduction amounts of C92 on the bloom surface were calculated by Eq. (11). The soft reduction amount for single convex roll is 1.93, 1.26 and 2.87 mm, and the total amount is 6.06 mm. The industrial results with the above parameters are shown in Fig. 10. It is seen that the "V" segregation has been improved remarkably after CRSR. Furthermore, the thickness of V segregation zone on the bloom longitudinal section decreased from 36 to 16 mm.

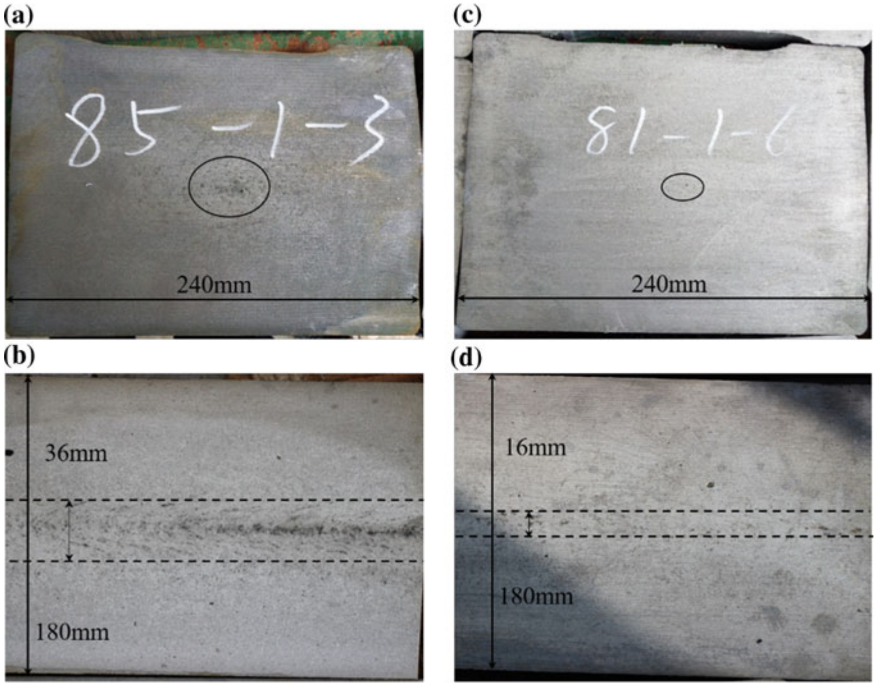

Fig. 10 Macrographs of transverse (**a**, **c**) and longitudinal (**b**, **d**) bloom section: **a** and **b** old soft reduction amount, **c** and **d** optimum soft reduction amount calculated by model

Conclusion

A 2D finite element model has been established based on thermal–mechanical coupled calculation for the determination of operation parameters of CRSR during bloom continuous casting. Two issues have been investigated in this study, the solidification shrinkage of the unmovable mushy zone and the reduction efficiency of the new roll. The shrinkage of the mushy zone is calculated by a theoretical model based on mass conservation during solidification. The total shrinkage area is about 75 mm^2 for the 180×240 mm^2 bloom with a casting speed of about 1.25 m min^{-1} in the suitable reduction range. The reduction efficiency of the convex roll is calculated on basis of the visco-elastic-plastic deformation behavior of the mushy zone. It decreases linearly from 31.7 to 4.7% when the center solid fraction of the reduction location increases from 0.3 to 0.6. The maximum stress is observed on the bloom surface where the strand contacts to the chamfer of the convex roll, while the maximum plastic strain appears in the inner-arc mushy zone. The total soft reduction amount suggested by the present model is 6.06 mm. It is noticed that the center segregation and “V” segregation have been improved remarkably by CRSR.

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